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LCA of renewable energy for electricity generation systems—A review

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ABSTRACT

Sustainable development requires methods and tools to measure and compare the environmental impacts of human activities for various products (goods and services). Providing society with goods and services contributes to a wide range of environmental impacts. Environmental impacts include emissions into the environment and the consumption of resources as well as other interventions such as land use, etc. Life cycle assessment (LCA) is a technique for assessing environmental loads of a product or a system. The aim of this paper is to review existing energy and CO_2 life cycle analyses of renewable sources based electricity generation systems.

The paper points out that carbon emission from renewable energy (RE) systems are not nil, as is generally assumed while evaluating carbon credits. Further the range of carbon emissions from RE systems have been found out from existing literature and compared with those from fossil fuel based systems, so as to assist in a rational choice of energy supply systems.

Contents

1. Introduction: LCA methodology

Life cycle assessment (LCA) is a technique for assessing various aspects associated with development of a product and its potential impact throughout a product's life (i.e. cradle to grave) from raw material acquisition, processing, manufacturing, use and finally its disposal [1]. LCA studies should systematically and adequately address the environmental aspects of products/systems. The depth of the details and time frame of an LCA study may vary to a large extent, depending on the definition of goal and scope. The scope, assumptions, description of data quality, methodologies and output of LCA studies should be transparent. LCA methodology should be amenable to inclusion of new scientific findings and improvements in the state-of-the-art of the technology. The strength of LCA is in its approach to study in a holistic manner the whole product/system and enables us to avoid the sub-optimization that may be the result of only a few processes being focused on. The results are also related for the use of a product, which allows comparisons between alternatives. Life cycle assessment (LCA) includes definition of goal and scope, inventory analysis, impact assessment and interpretation of results as shown in Fig. 1 [2–4].

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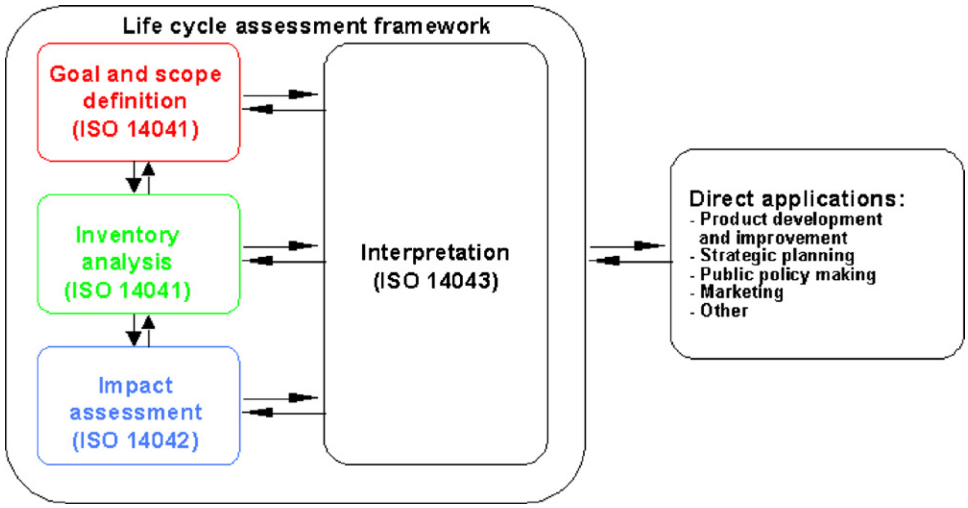


Fig. 1. Life cycle assessment framework [5].

The increased awareness of the importance of energy in our society and the growing concern over future sources of energy have led to inquiries as to how much energy is used in producing goods and services. An important application of LCA is net energy analysis. Net energy has been defined as the amount of energy that remains for consumer use after the energy costs of finding, producing, upgrading and delivering the energy have been paid [6]. If a new technology consumed more energy than it produced so that it had a net energy output negative, it could not provide any useful contribution to energy supplies and should be dismissed as a net energy sink. Conversely, if a new energy technology could achieve a positive net energy output when energy is in short supply, then it should be adopted for use even if the economic evaluation of its prospects is found to be unfavourable [7].

LCA is an instrument to quantify all impacts of the entire energy supply chain, e.g. to obtain the cumulative energy demand (CED) for production of a power plant, its life cycle carbon emissions, etc. The whole facility is split up into components and subcomponents and all energy and material flows through these are examined [8]. The life cycle impact of typical renewable energy systems is important when comparing them to conventional fuel-based systems for rational choice of energy sources. In addition to the well-known differences between conventional fuel based and renewable energy systems in economic impact, a number of stark differences in all other impact areas strongly favour the renewable energy solutions [9].

2. LCA of renewable energy systems

The LCA can be applied to assess the impact on the environment of electricity generation and will allow producers to make better decisions pertaining to environmental protection [10]. Tahara et al. [11] studied CO_2 payback time for future renewable energy electric power plants compared with commercial fossil fuel-fired electric power plants (coal, oil and LNG) in order to estimate CO_2 reduction potential of renewable energy. Kreith et al. [12] estimates the lifetime CO_2 emissions from coal-fired, PV and solar thermal power plants in the US. These CO_2 estimates are based on a net energy analysis derived from both operational systems and detailed design studies. The system wise detailed study is as follows.

2.1. Wind energy system

Haack [13] calculates the energy cost of energy from a small wind electric system using the methodology employed by Pilati and Richard [14] in examining electricity generating systems. This methodology requires the calculation of the energy to construct and operate electricity generating systems but does not consider the energy required to dispose of a generating plant or its waste products. Input energy values include direct energy as well as indirect energy. Direct energy is like coal for fueling a coal fired power plant where as indirect energy is the energy embodied in manufacturing the components in an electricity generating system. Indirect energy costs are quantified by the use of energy values assigned to 357 sectors of the United States economy. These energy values are calculated from economic input–output tables. These tables are expressed as British Thermal Units (BTU) per dollar value of final product.

The small wind electric conversion system examined in this study consists of a 3 kW rated wind generator on a 20 m tower with a 400 Ah battery storage system and an electrical current inverter. The energy cost of power from the small wind electric system in this study is 1.92 BTU of primary energy input for every BTU of electrical output. This value is the ratio of small wind electric system input energy, 5.96×10^8 BTU of primary energy, to output energy of 3.1×10^8 BTU of electricity.

Schleisner [15] studied the assessment of energy and emissions related to the production and manufacturing of materials for an offshore wind farm as well as wind farm on land. The energy production over the lifetime of the wind farms has been estimated in order to calculate the energy pay back time of the wind farms. The wind farms analysed are an off-shore wind farm consisting of 10, 500 kW turbines with a total capacity of 5 MW, and a land based wind farm consisting of 18, 500 kW units with a total capacity of 9 MW. The turbines are three-bladed off-shore pitch regulated machines, each with a capacity of 500 kW at a nominal wind speed of 16 m/s. The tower height is 40.5 m and the rotor diameter is 39 m. The primary energy used in the production and disposal of materials comprising off-shore wind farm is 43,873 GJ. The yearly electricity production of 12,500 MWh of the wind farm is converted to primary energy that would be consumed at a conventional power plant in order to estimate the energy pay back time. Based on an estimated efficiency of 40%, the energy use is paid back in 0.39 year or less than 2% of a 20-year life time for off-shore wind farm, emissions are 16.5 g-CO_2/kWh, 0.03 g-SO_2/kWh and 0.05 g-NOx/kWh and for the land based wind farm the corresponding figures are 9.7 g-CO_2/kWh, 0.02 g-SO_2/kWh and 0.03 g-NOx/kWh, respectively.

Jungbluth et al. [16] modeled wind turbines of 600 kW, 800 kW and 2 MW as for European onshore conditions. The full life cycle

inventories with the unit process raw data for all production stages can be found in the Ecoinvent database. The capacity factor depends on the site conditions and the characteristics of the wind turbine. For Switzerland, the capacity factor of the single modeled wind power plants are calculated using electricity production statistics of recent years in order to have a sort of average values. The 2 MW turbine causes higher emissions than the 800 kW turbine. In both cases, the largest contribution originates from material manufacturing. The absolute values of these greenhouse gas emissions are about 11 g-CO_2/kWh for the onshore and about 13 g-CO_2/kWh for the off-shore turbine.

Lenzen and Munksgaard [17] review existing energy and CO_2, life-cycle analyses of wind turbines in order to determine the causes for the widely varying results of earlier studies. In this survey energy and CO_2 analyses of wind turbines is presented considering the influence of different parameters like life time, load factor, power rating, country of manufacture, etc. Lenzen and Wachsmann [18] examined the energy and CO_2 embodied in a particular wind turbine manufactured in Brazil and in Germany. The wind turbine model E-40 manufactured by the German company Enercon features a three blade, pitch controlled rotor with a nominal power of 500 or 600 kW. Both countries feature a large consumption of oil-based liquid fuels. While natural gas and nuclear energy are only important for German industries, hydraulic energy, bagasse and firewood, and sugarcane based alcohol are unique to Brazil. In this five scenarios had been examined and for each scenario, they considered five installation options featuring different locations (with different tower heights and foundation masses). For the hypothetical scenario it has been assumed that 75% of Brazil's steel production is from scrap steel is the electric arc furnace (ESF) and 25% from primary ore via the basic oxygen furnace (BOF). Table 1 shows a country wise overview of energy and CO_2 analysis of wind turbines.

2.2. Solar photovoltaic system

Photovoltaic (PV) technology is expected to be a leading technology to solve the issues concerning the energy and the global environment due to several advantages of the PV system.

Schaefer and Hagedorn [25] carried out a comparative analysis of the surface and material requirements of different power stations. The accumulated energy consumption (hidden energy or grey energy) in the manufacturing and construction of photovoltaic power plants, CO_2 emissions caused by photovoltaic power generation and the energy amortization time (energy pay back time) were evaluated. The accumulated primary energy consumption for the construction of the Photovoltaic power plants ranges from 13,000 to 21,000 kWh/kWp and represents the lowest threshold for the current state of the art. It may be accepted that the values would varied between 7000 and 12,000 kWh/kWp, which could be achieved in the coming 5 years with technological improvements and an increase in production rates at the same time. In this study the 0.62 kg-CO_2/kWh were taken as specific emission factor for the accumulated final energy consumption of electrical energy. The CO_2 emissions are 3.360 kg-CO_2/kWp and 5.020 kg-CO_2/kWp for amorphous and mono-crystalline technology, respectively.

Prakash and Bansal [26] carried out energy analysis of solar photovoltaic module production in India. Monocrystalline wafers of p-type silicon are imported for cell and module production in India. The energy payback period of a mono-crystalline SPV module in India was evaluated as approximately 4 years.

Kato et al. [27] have done a life cycle analysis of single-crystalline silicon (c-Si) photovoltaic cells and residential PV systems using off-grade silicon supplied from semiconductor industries. This study was done for a 3 kW residential PV system installed on the roof top. The residential PV system was assumed to be connected to the utility grid without a battery and installed where solar radiation is 1427 kWh/m^2 year. Annual electrical output of the PV system is calculated at 3.47 MWh/year. Balance of system (BOS) of the residential PV system consists of supporting structure and an inverter. The indirect CO_2 emissions of the PV systems using the c-Si PV cells made up of the off grade Si was estimated at 91 g-CO_2/kWh.

Alsema [28] studied the energy requirements and CO_2 emissions for the production of PV modules and BOS components of grid connected PV systems. Both c-Si and thin film module technologies are investigated. The energy pay back period was found to be 2.5–3 years for roof top installation and 3–4 years for multi-megawatt ground mounted system. The CO_2 emissions of the rooftop system were calculated as 50–60 g/kWh now and probably 20–30 g/kWh in the future.

Mason et al. [29] study relates to a life cycle analysis of the balance of system (BOS) components of the 3.5 MWp multi-crystalline PV installations at Tucson Electric Power's (TEP) Springville, AZ field PV plant. TEP instituted an innovative PV installation program guided by design optimization and cost minimization. TEP has designed the Springville PV plant for 8 MWp. 4.6 MWp of PV modules has been installed, of which 3.5 MWp is framed mc-Si and 1.1 MWp is frames and frameless thin-film PV modules. The life cycle energy uses and GHG emissions over the complete life cycle of PV BOS were determined from the commercial Life Cycle Inventory (LCI) databases, Franklin and Ecoinvent, public domain sources from National Renewable Energy Laboratory (NREL) and the Aluminium Association. Supplementary data sources include those from the US energy Information Administration the US department of energy. The total primary energy in the BOS life cycle is 542 MJ/m^2 of installed PV

Table 1
Overview of energy and CO_2 analysis of wind turbines

S. no.	Year of study	Location	Power rating (kW)	Life time (years)	Energy intensity (kWh/kWh)	g-CO_2/kWh
1	1997 [19]	Denmark	30	20	.1	NA
2	1996 [20]	Japan	100	20	.456	123.7
3	2001 [18]	Brazil	500	20	.069	NA
4	1999 [21]	India	1500	20	.032	NA
5	1996 [22]	UK	6600	20	NA	25
6	2001 [23]	Japan	100	25	.160	39.4
7	2005 [24]	Japan	300	NA	NA	29.5
8	1981 [13]	USA	3	NA	1.016	NA
9	2000 [15]	Denmark	10×500[a]	20	NA	16.5
			18×500[b]			9.7
10	2005 [16]	Switzerland	30–800	20	NA	11

[a] Off shore.
[b] On land.

Table 2
Overview of CO_2 analysis of PV system

S. no.	Year of study	Location	Type of cell	Power rating (kW)	g-CO_2/kWh
1	2005 [24]	Japan	a-Si	–	53.4
2	1992 [25]	Germany	c-Si	300/1500	250/150
3	1992 [25]	Germany	mc-Si	300/1500	250/110
4	1992 [25]	Germany	a-Si	300/1500	170/100
5	1997 [27]	Japan	c-Si	3	91
6	2000 [28]	Italy	c-Si and thin film	3300	50–60
7	2006 [30]	Singapore	c-Si	2.7	165
8	2005 [31]	Greece	mc-Si	3	104[a]
9	2005 [29]	US	mc-Si	3500	184 kg-CO_2/kWp

[a] Assuming life time 20 years.

modules and the energy pay back period is 0.21 year. The GHG emissions during the life cycle of the BOS are 29–31 kg-CO_2/m^2.

Kannan et al. [30] performed LCA and life cycle cost analysis for a distributed 2.7 kWp solar PV system operating in Singapore. In this study energy pay back time analysis of the solar PV system and their green house gas emission and costs are compared to a fuel oil-fired steam turbine. The 2.7 kWp solar PV system consists of 36 mono-crystalline modules (12 V, 75 Wp) mounted on a building roof top with aluminium supporting structures and concrete blocks for the base. The 12 modules are connected in series to generate 204 V DC at their rated voltage. All indicators of the study such as energy use, emissions and cost are indexed based on the functional unit which is defined as 1 kWh of AC electricity. The life cycle energy use would reduce to 2.2 MJ/kWh and the EPBT would be 4.5 years. The GHG emissions would be about 165 g-CO_2/kWh.

Tripanagnostopoules et al. [31] carried out an LCA study on PV and PV/T system using SimaPro 5.1 software determining two payback time parameters. The energy payback time (EPBT) and the CO_2 pay back time (CO_2 PBT). The study focuses on a 3 kWp PV or PV/T system with an active surface of 30 m^2 with multi-crystalline silicon PV modules. The best case is PV/T with glazing (with or without reflectors) operating at the lowest temperature (25 °C) shows payback period of 0.8 year. Table 2 shows a country wise overview of CO_2 analysis of PV system.

2.3. Solar thermal system

Lenzen [32] explores ways of determining the greenhouse gas cost of electricity generation technologies. In these different approaches for calculating GGC, their characteristics, and their short comings are appraised. Thereafter these methods are applied to three types of solar power plants: parabolic trough, central receiver and parabolic dish, as well as to some fossil systems for comparison. Five different aspects of their greenhouse gas analysis are treated the effect of the choice of method on the result for a given plant, the effect of fossil fuel back up on the plant GGC, economies of scale and a comparison with recent greenhouse gas analysis of other electricity generating systems.

The environmental impact arising from the production of electricity from a 1 MW solar thermal plant and the technology used is based on a paraboloidal disc. The plant consists of 17 big solar discs generating steam to drive an engine. The steam generated by collectors is used to drive 5 Stirling engines to produce electricity [33]. A 17 MW solar thermal power plant with central tower technology and 2750 heliostats use molten salt to provide 16 h of stored energy. A 50 MW solar thermal power plant with parabolic troughs technology consisting of 624 parabolic troughs collectors that uses synthetic oil as transfer fluid and molten salts for 7 h storage system [34]. Table 3 shows a country wise overview of CO_2 analysis of solar thermal system.

2.4. Biomass system

Hartmann and Kaltsschmitt [35] studies the environmental effects of electricity production from different biofuels by means of co-combustion with hard coal in existing coal fired power plants are analysed and compared to electricity production from hard coal alone based on LCA. In the study use of straw and residual wood at a 10% blend with coal in an existing power plant in the southern part of Germany. The emissions of CO_2 equivalents for the provision of electricity from biomass are much lower compared to that from hard coal.

Rafaschieri et al. [36] analysed the environmental impact of electric power production through an integrated gasification combined cycle (IGCC) fired by dedicated energy crops (poplar short rotation forestry (SRF)) by life cycle approach. These results are compared with the alternative option of producing power by conventional fossil fueled power plants. As a model for the impact evaluation the Eco-indicator methodology was applied. This method has been developed within the National Dutch Programme about waste recycling. The biomass production cycle is based on harvesting 2-year-old poplar trees. SRF is preceded by a 3-year nursery cultivation aimed at production of cuttings. The achievable biomass yield is estimated to be about 20 dry Mg/ha/year. The net available quantity of biomass is about 16 dry Mg/ha/year as a result of natural drying during stockage. For transportation of biomass Diesel-trailers (40 Mg load) were used and the average distance of the biomass stock to the power plant was assumed to be 75 km energy consumption and emissions caused by extraction, processing, transport and combustion of fuel for transport were completely taken into account. A low or medium heating value gas is produced by a pressurized fluid bed (PFB) gasifier with an air or oxygen stream (steam injection is not necessary because of the biomass humidity). The LHV of the gas is sensitive to both the oxidizing agent and biomass humidity. The gasifier includes mechanical filters and an effective cyclone for removing large particles from the gas. A further filtration step is also necessary in order to remove fine particles (smaller than 10 μm) which should not be ingested by the gas turbine. The biomass is used as a fuel in a gas/steam combined cycle power plant. The biomass production amounts 7330 kg-CO_2 emission per ha per year as a whole.

Table 3
Overview of CO_2 analysis of solar thermal system

S. no.	Year of study	Location	Type	Life time (years)	Power rating (MW)	g-CO_2/kWh
1	2006 [33]	Italy	Paraboloidal dish	30	1	13.6
2	2006 [34]	Spain	Central tower	25	17	202
			Parabolic trough	25	50	196
3	1990 [11]	US	Central receiver	30	100	43

Table 4
Overview of CO_2 analysis of biomass system

S. no.	Year of study	Process	Power rating	g-CO_2/kWh
1	2004 [39]	Coal system + biomass co-firing and CO_2 sequestration	457 MW	43
2	2005 [38]	IBGCC + CO_2 removal (chemical absorption)	204.5 MW	178
3	2005 [40]	Biogas cogeneration	80 kW	78
4	1999 [35]	90% hard coal and 10% straw	509 MW	37
		90% hard coal and 10% wood		35
5	1999 [36]	IGCC	1 MWh	110

Corti and Lombardi [37] done performance analysis and life cycle assessment of an integrated gasification combined cycle (IGCC) fed with biomass with upstream CO_2 chemical absorption. In the simulation an atmospheric gasifier has been modeled, fed with 31 kg/s biomass mass flow. The biomass considered is dry poplar, characterized by a carbon/hydrogen ratio of 8.28 and a LHV of about 18,000 kJ/kg. Greenhouse effect values for the different considered phases in terms of kg of CO_2 equivalent per functional unit (1 MJ of energy produced). The results are compared with the IGCC with De CO_2 where CO_2 reduction at the stack is obtained by means of amine solution chemical absorption. An IBGCC with CO_2 chemical absorption form the syn gas has been simulated by means of Aspen Plus. Results are 167 kg-CO_2/MWh with respect to conventional coal IGCC 700–800 kg-CO_2/MWh and NGCC 380 kg-CO_2/MWh.

Carpentieri et al. [38] studied the life cycle assessment of an integrated biomass gasification combined cycle (IBGCC) with CO_2 removal by chemical absorption. In this an LCA was conducted with presenting the results on the basis of the Eco-indicator 95 impact assessment methodology. The aim of this work is to assess the environmental impact, on a life cycle horizon, of biomass utilization in energy production. The contributions of the different life cycle phases to the overall impacts are highlighted in order to assess the phases of most impact. Further a comparison with an analogous LCA study of a similar energy conversion cycle fed with coal (ICGCC) was examined. The simulated result of this IBGCC specific CO_2 emissions are 178 kg-CO_2/MWh. Table 4 shows a country wise overview of CO_2 analysis of biomass system.

2.5. Hydro power

Hydel energy generation is expected to increase from 1953 TWh in 1984 to about 7680 TWh by 2020 AD and a major portion of this growth is expected to take place in the developing countries [41]. The development of hydroelectric power throughout the world is receiving renewed attention as the economic, political and environmental costs of conventional energy production rise. Gleick [42] compare the environmental and ecological impacts of small and large hydroelectric generation systems with a focus on land requirements, evaporative water losses, seepage and sedimentation.

Gagnon and Vate [43] reports on the findings of a recent International Atomic Energy Agency (IAEA) expert meeting on the assessment of greenhouse gas emissions from the full life cycle of hydro power. It discusses the different categories of hydro power plants in view of the three main sources of GHG emissions. One of the emissions associated with the construction of the plant, second emission from decaying biomass from land flooded by hydro reservoirs and the third is thermal back up power. If the production of a given hydro power plant is entirely seasonal notably for most run-of river plants, the back up generation of electricity (required to compensate) should be included in the assessment. There are certain factors without including these factors the study could not be completed. The factors are run-of river plants versus plants with reservoir, material used earth/rock versus reinforced concrete, volume of the dams and dikes, which are site specific and the overall size of the project. The amount of materials required for construction of hydro power plants. These materials are mainly steel and concrete/cement. Run-of river plant require much less material per unit of energy. The site-specific character of the construction activities results in a substantial range of assessments (1–10 g-CO_2/kWh). When a hydro reservoir is created, the newly flooded biomass will decay and the process will gradually release some greenhouse gases. Many factors can affect GHG emissions from decaying biomass and the size of the reservoir is a major factor. Therefore run-of river plants do not produce significant GHG emissions. Hydro power plants in humid tropical countries have a potential for high GHG emissions because of the following conditions. High quantities of biomass per ha, biomass that is mostly in the forest cover and not in deep soils, warm conditions with decomposition process at work 12 months per annum. With the extreme assumptions that 100% of flooded biomass would decompose over 100 years and that 20% of biomass carbon would be emitted as CH_4 the emission factor for Tucurui (power plant) would be 237 g-CO_2 equiv./kWh, a factor that is several times lower than modern fossil fuel options. Table 5 shows a country wise overview of CO_2 analysis of hydro system.

3. Comparison with conventional systems

Table 6 [46] shows the life cycle emissions for various conventional fuels for electricity generation and the maximum emission for the coal-fired plant is 975.3 g-CO_2/kWh and minimum for the nuclear power plant, which is around 24.2 g-CO_2/kWh. Table 7 shows comparison between renewable electricity generation technologies and the conventional electricity generation sources. The life cycle emissions are comparatively very high in conventional sources as compared to renewable sources. In conventional sources only nuclear-based power electricity generation has fewer emissions to the environment but the dumping of the radioactive material causes higher damage to the surroundings.

Table 5
Overview of CO_2 analysis of hydro system

S. no.	Year of study	Location	Type	Life time (years)	Power rating (MW)	g-CO_2/kWh
1	1997 [43]	Japan	Reservoir	100	4000	237
2	1996 [44]	Switzerland	Run-off-river	80	3.2	3.7
			Storage	70–200	8.6	4.5
3	1996 [45]	Japan	Run-off-river	30	10	18

Table 6
Comparison of LCEs (g-CO_2/kWh) of conventional electricity generation techniques [46]

Phases of LCA	Coal fired	Oil fired	Gas fired	Nuclear
Fuel combustion	886.8	704.3	477.9	–
Construction	3.6	2.3	2.9	2.8
Operation	32.0	35.2	117.7	20.9
Decommissioning/methane leakage[a]	52.9	0.3	9.1	0.4
Total	975.3	742.1	607.6	24.2

[a] For nuclear power decommissioning in place of methane leakage.

Table 7
Comparison of LCEs (g-CO_2/kWh) of conventional electricity generation with renewable electricity generation sources

S. no.	Conventional systems		Renewable systems	
	System	g-CO_2/kWh	System	g-CO_2/kWh
1	Coal fired	975.3	Wind	9.7–123.7
2	Oil fired	742.1	Solar PV	53.4–250
3	Gas fired	607.6	Biomass	35–178
4	Nuclear	24.2	Solar thermal	13.6–202
			Hydro	3.7–237

4. Conclusions

A general tendency in the results for the above studied systems is clearly in favour of renewable energy technologies. Comparing for the best place among the renewable energy sources, it is observed that small hydro (run of types) schemes (in which there is no storage of water) tends to be most attractive but site dependent. For an optimum selection of the electricity sources there should be some mixed technologies so that load on environment can be reduced and electricity distribution is possible. This study further point out that some renewable energy systems, e.g. solar PV can produce significant lifecycle carbon emissions and this fact should be accounted for in evaluating carbon credits available from such systems.

Appendix A

A.1. Energy pay back time

Energy pay back time (EPBT) means years to recover primary energy consumption throughout its life cycle by its own energy production. Both the total primary energy requirement and annual power generation concerned primary energy. Energy pay back time (year) of a system is a ratio of Total primary energy requirement of the system throughout its life cycle to annual primary energy generated by a system. To convert annual power generation (kWh) of electricity to primary energy looked at the efficiency of power plants in the assumed country.

A.2. CO_2 pay back time

CO_2 pay back time (PBT) is calculated from estimates of CO_2 emissions from construction and during operation in a large scale of fossil fuel combustion during operation.

For example, the definition of CO_2 pay back time, for hydroelectric versus coal fired power plant is defined as follows:

$$CO_2PBT = \frac{[(C_{hydro}/E_{hydro}) - (C_{coal}/E_{coal})]}{[(O_{coal}/E_{coal}) - (O_{hydro}/E_{hydro})]}$$

where $C = CO_2$ emissions from material production and its construction (g-CO_2); $O = CO_2$ emissions from generating (operating) plant (g-CO_2/year); E = electricity generated annually (kWh/year).

A.3. Energy intensity

The energy intensity for a plant of power rating (P) and load factor (λ), is defined as the ratio of the energy requirement (E) for construction, operation and decommissioning and the electricity output of the plant over its life time (T).

$$\text{Energy intensity} = \frac{E}{P \times 8760 \times \lambda \times T}$$

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